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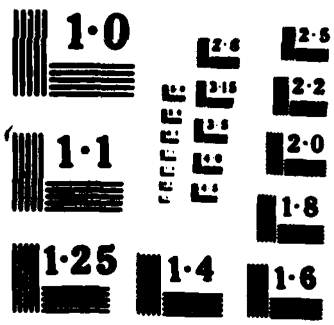
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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Analytical work devoted to the global acoustics has been concerned with both linear and nonlinear behavior. Good agreement has been found between calculations of the mode shapes and data taken at the Naval Weapons Center. Numerical calculations are in progress to provide representation of the nonlinear unsteady behavior of a normal shock wave in an inlet diffuser, including viscous effects.

Experimental investigations of combustion have been carried out with pressure, spectral line intensity and flow visualization techniques in a burner equipped with a bluff body flameholder. When the combustion is stable, the flow in the flameholder shear layers has many of the characteristics of isothermal shear layers. When unstable combustion occurs, the shear layers are characterized by large vortices which are shed from the flame holder lip. The self excited oscillations appear to result from a coupling between the vortex production mechanism and nonsteady heat addition in the

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vortex. Both steady and nonsteady processes are being studied.

Calculations of the pressure pulse from a flame wound in a plane vortex have been completed and show the manner in which the pressure peak and time delay scale with system variables.

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Mechanisms of Exciting Pressure Oscillations in Ramjet Engines

I. RESEARCH OBJECTIVES

This report covers the third year of a program concerned with the mechanisms for low frequency pressure oscillations in ramjet engines. Both analytical and experimental work are included. The analysis covers both detailed examination of specific mechanisms and the acoustical framework within which the relative influences of various mechanisms may be assessed. The experimental work is initially being performed in a small scale laboratory dump combustor. Subsequent tests related to the problem of scaling will be carried out in a larger facility at the Air Force Aero Propulsion Laboratory.

A. Analytical Work

1. Modelling the Steady Flow Field in a Dump Combustor

As part of the basis for carrying out analysis of the unsteady motions, it is necessary to have a model of the steady flow field. The purposes of the present program, items 2 and 3 below, will be adequately served by a relatively crude approximation to the actual field. We intend to assume that combustion occurs in a flame sheet anchored at the dump plane. Ignition of the incoming flow is sustained by hot gases supplied from the recirculation zone which is separated from the main part of the chamber by a shear layer. We shall approximate the shear layer as an infinitesimally thin discontinuity of velocity. To the greatest extent possible, integral methods will be used to formulate approximate solutions for the various regions of the chamber. Errors in the representation of the steady flow field can be tolerated because the results will appear only as parts of integrals in the analysis of the acoustic field.

2. Analysis of the Linear Acoustic Field

The description of the acoustic field will be constructed in the manner used to analyze corresponding problems in liquid and solid rockets. Modifications will be required to accommodate the strong gradients of the average temperature and velocity fields. Moreover, account must be taken of the inlet shock system and the high speed flow in the inlet.

3. Analysis of Nonlinear Acoustics

Approximate techniques, developed and used for studying pressure oscillations in solid propellant rockets, will be used to analyze non-linear behavior in ramjet engines. The ultimate purpose is to understand the processes responsible for limiting the amplitudes of steady oscillations. The nonlinear behavior of a shock wave in a diffuser will be treated numerically to provide the upstream boundary condition for the acoustics field.

4. Comparison With Data

Results of the analyses will be used to correlate and interpret data. In addition to data acquired in the present program, we shall be supplied with observations and measurements taken with a laboratory combustor operated at the Naval Weapons Center, China Lake. Predicted behavior of the shock wave in a diffuser will be compared with data taken at NWC and at the McDonnell-Douglas Research Laboratory.

5. Analysis of Non-steady Combustion Fields

The work concerning the behavior of flames and combustion in vortex structures has revealed a surprising order and simplicity of the overall reactant consumption rate, in contrast with the general complexity of the gas-dynamic field. Most of the results to date (i) deal with initially un-mixed gaseous reactants, (ii) treat the field of a single vortex rather than a group of interacting vortices and (iii) do not treat the development

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of concentrated reacting vortices from reacting free shear layers. Each of these items underlies an essential novel process in reacting gas-dynamics.

The novel feature of the vortex combustion of pre-mixed reactants lies in the quite different behavior of premixed flames, under conditions of straining and extension, from diffusion flames. These differences have important implications in the time-dependent behavior of overall combustion rate as a function of time. This time dependent combustion pulse is one of the fundamental concepts of reacting gasdynamics and is an essential element in high frequency instability mechanisms.

Studies of multiple vortex structures will be started this grant year by considering the plane vortex pair and the annular (ring-shaped) vortex. The thorough understanding of their combustion characteristics is essential in the understanding of non-steady combustion of jets and slot burners. Moreover it constitutes the first step in fundamentals of non-steady combustion in complex gas-dynamics fields. Studies of a vortex pair, situated on the boundary of a fuel strip and a strip of pre-mixed reactants will be continued through the next grant period with a reasonable expectation of completing work on the vortex pair.

Two specific mechanisms for self-excited combustion oscillations were proposed at the initiation of this grant. The first was associated with vortex shedding from flame holding devices, the vortex shedding being forced by the acoustic oscillations that were, in turn, excited by the delayed combustion of these vortex structures. The frequencies of these oscillations is in the kiloherts range and involves, in an essential way, the interaction between flame chemistry and flame straining rate. The second has to do principally with the Kelvin-Helmholtz instability of vortex sheets shed from curved flame fronts. This unstable flow distorts further the flame front augmenting the strength of the vortex sheet and feeding the Kelvin-Helmholtz instability. During the next grant period this mechanism will be developed for pre-mixed reactants.

B. Experimental

The general objectives of the experimental program are to acquire data concerning unstable combustion so that we can obtain a better understanding of this phenomenon in general. The system used in this study is a simple model of a dump burner configuration such as that which would be used in a ramjet system, but the results will be more generally applicable to any system utilizing a bluff body type of flame holder.

The experiments are being carried out in a premixed stream of fuel and air and methane is the fuel. A small blowdown facility is being used and the instrumentation includes time and space resolved measurements of the pressure and the intensity of radiation from several spectral bands. Flow visualization techniques include the use of shadowgraph photographs with both microsecond duration spark light source and high speed movies. Simultaneous measurements of light intensities and pressure fluctuations at a number of positions in the duct allow us to obtain the good qualitative picture of the interaction between pressure and heat release fluctuations which is required for the development of physical models for the instability process.

Changes in the acoustic damping of various parts of the supply system allow us to determine the response of the combustion process to pressure perturbations with a range of frequencies.

Data are acquired at a rate of 5kHz per channel and spectral analyses of several types are being carried out.

II. STATUS OF RESEARCH

A. Analytical Work

1. Modelling the Steady Flow Field in a Dump Combustor

The modelling of the steady flow field was completed during the second year and numerical results have been obtained. It is convenient to divide a complete engine into three parts: the inlet duct, the main combustion region in the combustor, and the zone within the combustor but downstream of the combustion zone. With the assumption that both the flame sheet and the shear layer are adequately represented as infinitesimally thin sheets, the combustion zone comprises three regions: the unburnt flow of reactants upstream of the flame, and the recirculation zone also containing products of combustion.

An integral method has been used to treat the flows upstream and downstream of the flame sheet. The solutions are matched at the flame sheet. As an approximation, the vorticity is assumed uniform within the recirculation zone. Solution for the velocity field is then obtained numerically, and matched to the flow of combustion products at the shear layer.

The results have shown reasonable behavior for the shape of the flame sheet and of the surface representing the shear layer. The solutions appear to be relatively insensitive to the value assumed for the vorticity in the recirculation zone.

2. Analysis of the Linear Acoustic Field

A computer program has been written and preliminary numerical results have been obtained for the linear acoustic field in an entire engine. The boundary condition at the inlet is given by a previous analysis of the normal shock, completed in the first year of this program. Results for the amplitude and phase distributions for the pressure field in the inlet agree satisfactorily with measurements taken at the Naval Weapons Center. One example of the amplitude distribution in the combustion chamber also shows fairly good agreement with observations.

The representation we have used for unsteady combustion processes is incomplete. As a result, all modes of oscillation are predicted to be stable. This part of the problem must be improved during the coming year.

These results were reported at the AIAA Aerospace Sciences Meeting (January, 1983) and at the JANNAF Propulsion Meeting (February, 1983). More recent work will be discussed at the 1983 JANNAF Combustion Meeting and at the 1984 AIAA Aerospace Sciences Meeting.

3. Analysis of Nonlinear Acoustics

Some of the effort during the first two years of this program was devoted to approximate analysis of nonlinear behavior. Primarily, we were concerned with problems relating to the existence and stability of limit cycles. Some of the results obtained were reported at the 1983 AIAA Aerospace Sciences Meeting. More recent work will be discussed at the 1984 AIAA Aerospace Sciences Meeting. Support of that work has been transferred to another program.

During the past year, we have carried out numerical analysis of the behavior of a normal shock wave in a duct. The eventual purpose is to represent the unsteady behavior of a shock, including the effects of viscous boundary layers and shock/boundary layer interaction. To date we have obtained good results for the steady and unsteady behavior of a shock wave with no viscous effects; and for a steady shock wave including viscous effects with attached boundary layers.

This work will be reported at the 1983 JANNAF Combustion Meeting.

4. Vortex Combustion with Finite Reaction Rates

High frequency instability, that is in the range of 2kHz or above, almost always involves a chemical time delay as an essential feature in the mechanism. This result has been documented thoroughly in reference 1. In the example of reference 1 the shear layer separating from the sharp lip of the flame stabilizer is formed into a vortex and the time delay is a rather complex competition between the flame straining during the rolling-up process and the chemical reaction rates within the shear layer that is being rolled up.

To examine this process, the combustion process in a vortex with finite reaction rates has been carried out and appropriate amplification ratios and time delays have been computed, reference 2. The results show a growth rate over a time of the order of τ_c where τ_c is the chemical time that occurs in the laminar flame speed $S_L = (\sigma/\tau_c)^{\frac{1}{2}}$, so that the time delay of the pulse is of the order of this chemical time. The amplitude of the pulse scales as $\Gamma^{2/3}\sigma^{1/3}$ and, since Γ increases directly as the through-flow velocity, becomes stronger for higher velocities. The dimensionless representation of this growth pattern is shown in figure 1.

The acoustic pulse generated by this non-steady combustion process has been calculated for a two-dimensional geometry, and is shown in figure 2. This representation is shown in terms of the retarded time,

$t - r/a$ where r is the distance from the vortex core. The pressure amplitude of the pulse scales as

$$(\alpha-1)\rho_0 \Gamma^{2/3} \sigma^{1/3} \sqrt{a/x}\, \tau_c$$

This result gives us the possibility of calculating whether such a process, in a combustor of particular geometry, will or will not result in unstable oscillations.

B. Experimental Work

During the third year of this program, we have been performing experiments in a facility which has a blowdown air-fuel system and a plenum chamber about 50 cm long and 15 cm in diameter which supplies a combustible gas to a combustion chamber. This chamber is a 2.5 by 7.6 cm in cross section and one meter in length. It has glass windows on the 2.5 cm high sides and pressure and other instrumentation ports on the 7.6 cm walls. Flame holders designed to simulate some of the features of a dump burner configuration spanning the 7.6 cm dimension are typically 15 to 20 cm long and are located with the dump plane some 40 to 50 cm from the down stream end of the combustion chamber.

We are studying combustion in this system with the instrumentation mentioned above and a few results will be described here. First, for a range of operating conditions, the combustion process is stable. Although longitudinal pressure oscillations are present, they have a low amplitude and only small disturbances in the flame front can be seen in the photographs. The pressure waves have a frequency corresponding to a longitudinal mode in the combustion chamber when it is viewed as a duct closed at the upstream or flameholder end and open at the exit. The disturbances in the flame front are located in the shear layer formed in the flow downstream of the lip of the flame holder. They appear to us to be similar to the growing vortices observed in a normal, isothermal shear layer which has been perturbed by periodic acoustic disturbances. Thus at some distance from the flame holder, the frequency at which the disturbances in the shear layer pass a fixed point (as observed by the photomultiplier technique) is equal to the frequency of the acoustic mode. This result is in keeping with what we would expect from isothermal results.

In contrast, at other operating conditions, the flow is distorted by self excited oscillations of large amplitude. This unstable mode is characterized by the presence of large amplitude acoustic disturbances and the shedding of large amplitude vortices from the flame holder lip. The vortices grow to a scale equal to the height of the duct H by the time they move 1H to 2H downstream of the lip.

The large amplitude acoustic disturbances appear to arise in our system because of a resonance between the acoustic field and the combustion process. A large amplitude pressure oscillation is produced in a resonant cavity of the supply system or combustion chamber and the interaction of this pressure field with the shear layer at the flame holder lip produces the large vortices. Combustion in the vortices produces the nonsteady pressure required to drive the cavity resonance. For example, the plenum chamber has a natural frequency of about 200 Hz. In one of the unstable operating modes, the pressure in the combustion chamber has a dominant frequency of 200 Hz and the vortices are shed at about 200 Hz or every 5 milliseconds. We expect that the unsteady pressure perturbation produced by the vortex formation will occur within a few milliseconds and hence could reinforce the pressure oscillation.

In support of this model we note that when the damping of the system at 200 Hz is greatly increased (by placing steel wool in the plenum chamber), this resonance is completely eliminated. The 200 Hz frequency observed in this case is unaffected by substantial changes in the velocity of the flow and, at certain speeds, by changes in the fuel-air ratio.

We are continuing to investigate this process to establish unambiguously the relationship between the resonator, the vortex shedding process and the combustion feedback mechanism. At present, it is clear that the process depends on the gas speed, fuel-air ratio, and the geometry of the supply duct and combustion chamber. In addition, we are also investigating instabilities which depend on the reflection of acoustic energy from a nozzle contraction.

Notation

a Acoustic velocity

$\dot{m}$ Reactant mass consumption rate per unit area in laminar flame front

p Gas Pressure

x Distance to point of pressure p

α Density ratio, unburned to burned gas

Γ Circulation of vortex shed by flame holder during oscillation. Dimensions $(\text{length})^2/\text{time}$.

ρ Mass density of gas

σ Thermal diffusivity of gas

Note: The thermal diffusivity σ has the dimension of $(\text{length})^2/\text{time}$ so that $\sqrt{\sigma/\tau_c}$ has the dimension of a velocity.

τ_c Overall characteristic time of laminar flame reaction; it includes all effects of mixture ratio, temperature, pressure, as well as absolute chemical reaction rates.

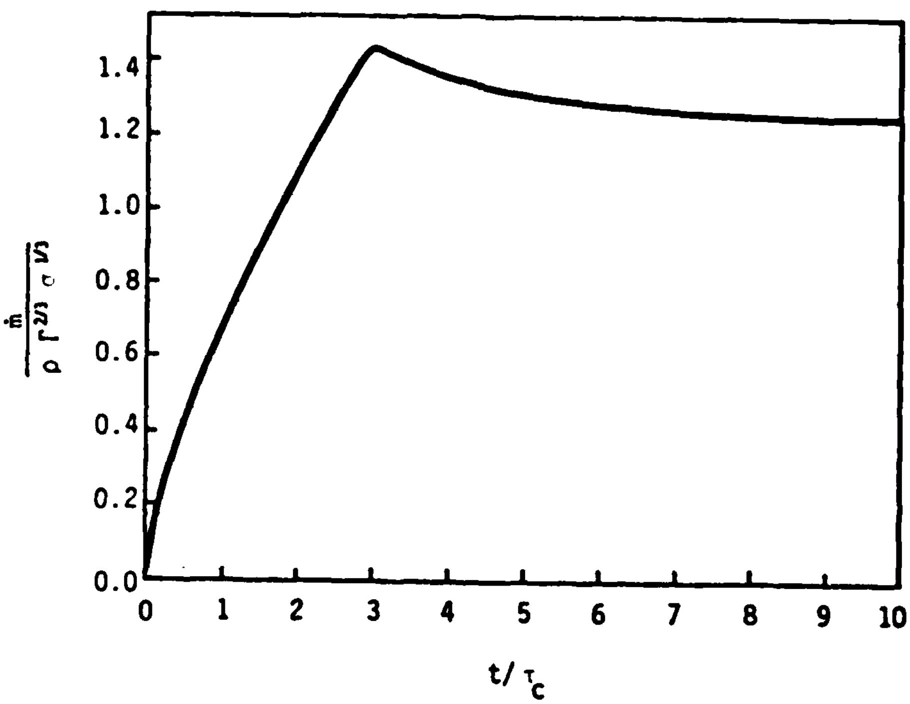

Figure 1. The augmented fuel consumption rate of the flame due to the presence of the vortex.

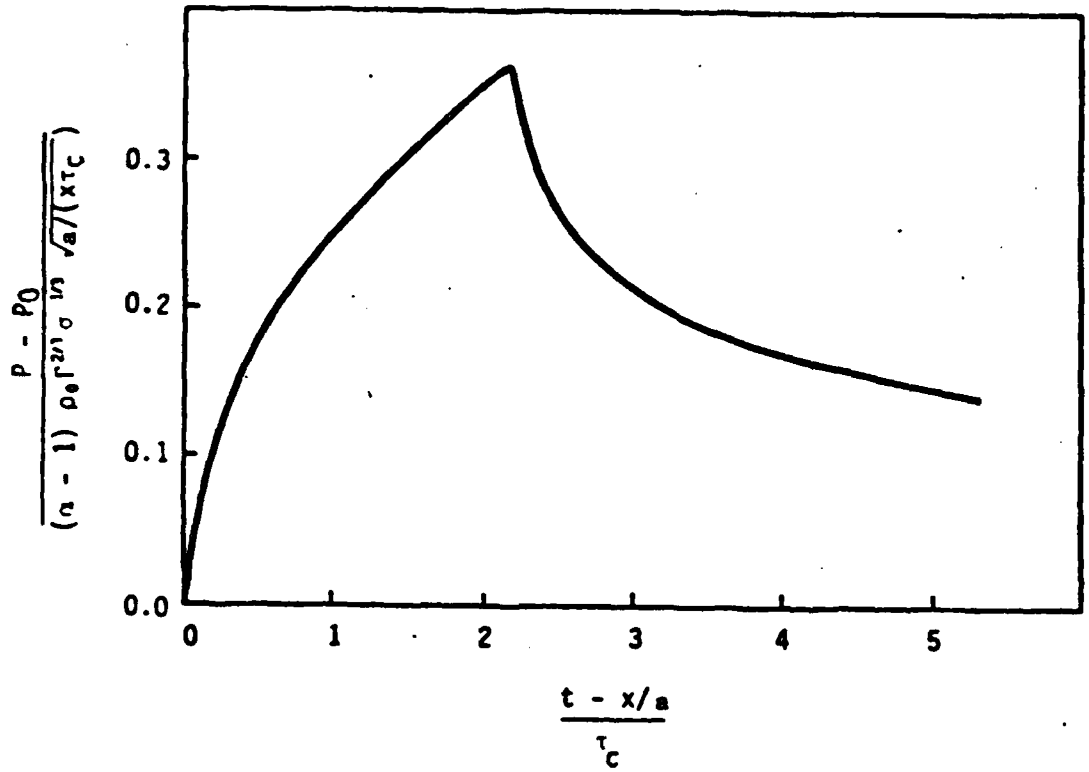

Figure 2. The pressure pulse seen at a distance x from the vortex, when x is large enough to lie in the far field.

III. PUBLICATIONS

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Karagozian, Ann R., "An Analytical Study of Diffusion Flames in Vortex Structures," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, 1982.

Norton, Olin P., "The Effects of a Vortex Field on Flames with Finite Reaction Rates," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, 1983.

Karagozian, Ann R., Marble, Frank E., "An Analytical Study of Diffusion Flames in Vortex Structures," International Combustion Institute, Western States Section, Pasadena, Ca.

IV. PERSONNEL

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V. REFERENCES

1. Rogers, D. E., Marble, F. E., "A Mechanism for High-Frequency Oscillation in Ramjet Combustors and Afterburners," Jet Propulsion, June, 1956.

2. Norton, Olin P., "The Effects of a Vortex Field on Flames with Finite Reaction Rates," PhD Thesis, California Institute of Technology, Pasadena, CA, 1983.

VI. INTERACTIONS WITH INDUSTRIAL AND GOVERNMENT RESEARCH GROUPS

Professor Culick has maintained continuing contacts with two groups at the Naval Weapons Center (Dr. K. Schadow and Dr. William Clark). A summary of their collaboration appeared in the proceedings of the International Symposium on Air Breathing Engines (ISABE) in June 1983. Professor Culick also continues exchange of information with groups at Wright Field, the Johns Hopkins Applied Physics Laboratory, and the McDonnell-Douglas Research Laboratory.

Professor Marble has a continuing association with NASA Lewis in the field of non-steady combustion, lean pre-mixed combustion and combustion-related turbine cooling problems. In addition he spends some time each year with the Gas Turbine Laboratory of the Massachusetts Institute of Technology on problems of combustion, turbomachinery instability, and combustion related turbine cooling problems. Professor Marble is a consultant to Northrop Aircraft on propulsion and combustion problems.